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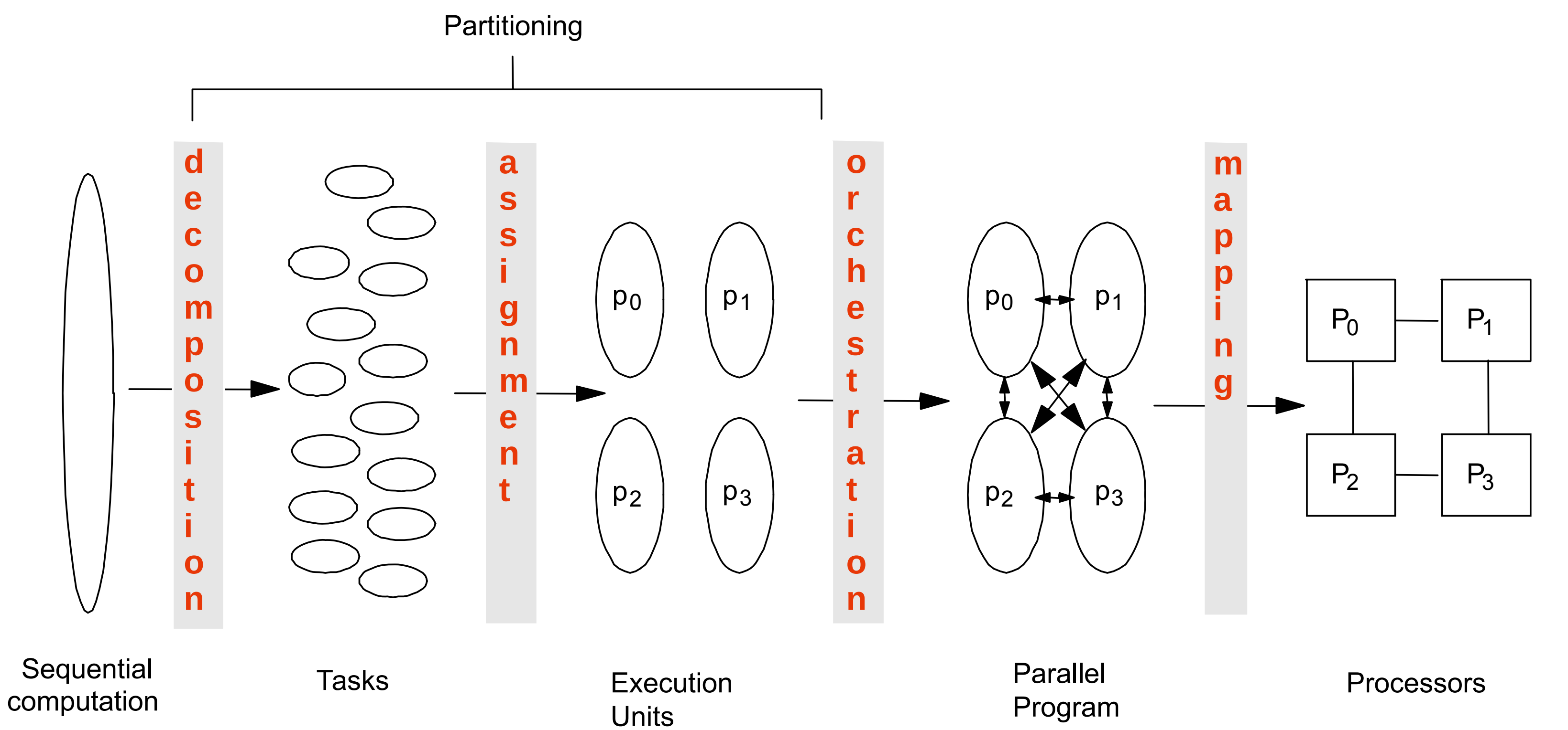
Lecture7

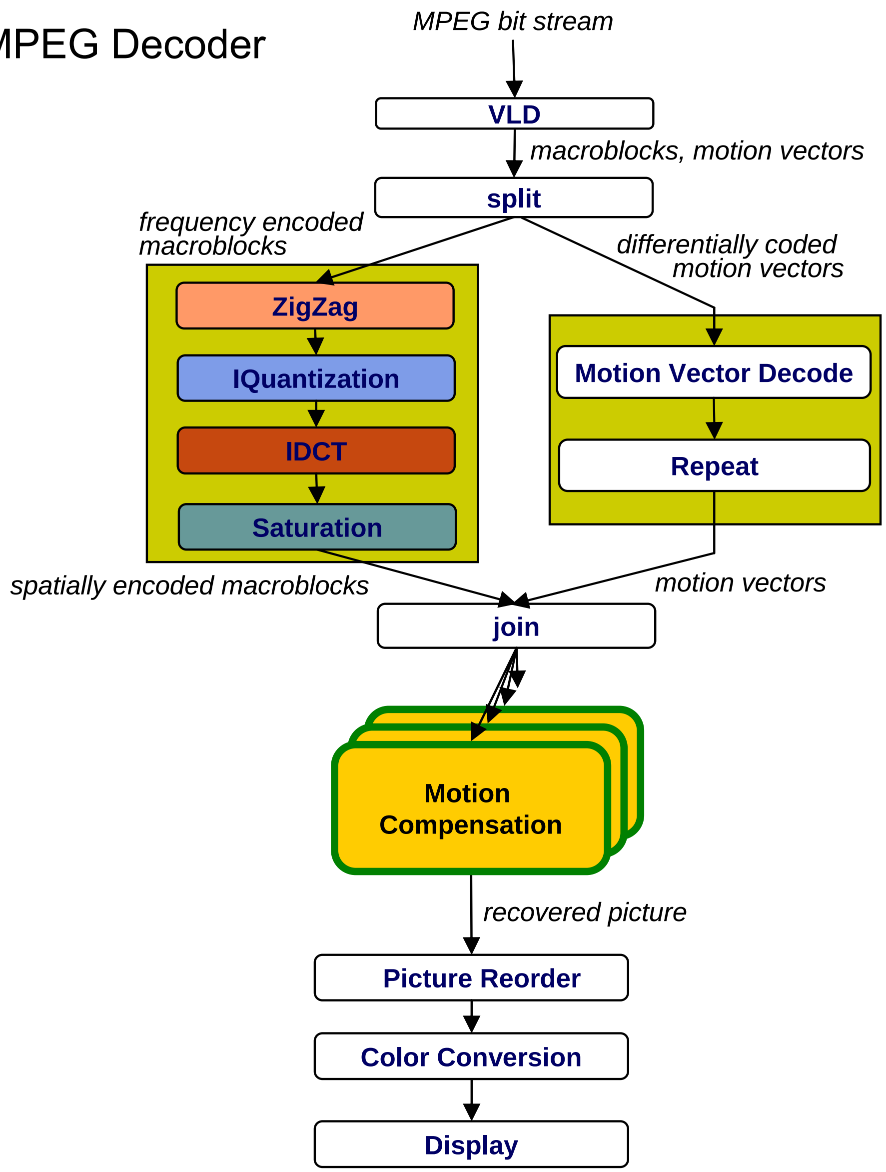
Design Patterns for Parallel Programming II

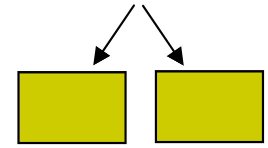
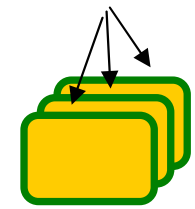
Recap: Common Steps to Parallelization

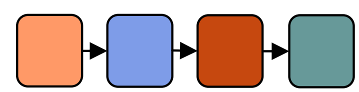


Recap: Decomposing for Concurrency

MPEG Decoder



- Task decomposition 
  - Parallelism in the application
- Data decomposition 
  - Same computation many data
- Pipeline decomposition
  - Data assembly lines
  - Producer-consumer chains



Dependence Analysis

- Given two tasks how to determine if they can safely run in parallel?

Bernstein's Condition

- R_i: set of memory locations read (input) by task T_i
- W_j: set of memory locations written (output) by task T_j

- Two tasks T_1 and T_2 are parallel if
  - input to T_1 is not part of output from T_2
  - input to T_2 is not part of output from T_1
  - outputs from T_1 and T_2 do not overlap

Example

T_1

a = x + y

T_2

b = x + z

$R_1 = \{ x, y \}$
$W_1 = \{ a \}$

$R_2 = \{ x, z \}$
$W_2 = \{ b \}$

$$R_1 \cap W_2 = \phi$$

$$R_2 \cap W_1 = \phi$$

$$W_1 \cap W_2 = \phi$$

Patterns for Parallelizing Programs

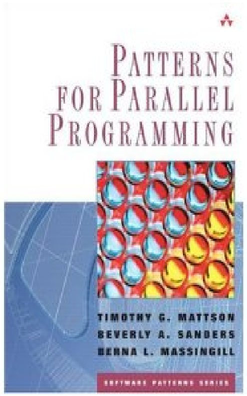
4 Design Spaces

Algorithm Expression

- Finding Concurrency
  - Expose concurrent tasks
- Algorithm Structure
  - Map tasks to units of execution to exploit parallel architecture

Software Construction

- Supporting Structures
  - Code and data structuring patterns
- Implementation Mechanisms
  - Low level mechanisms used to write parallel programs



Patterns for Parallel Programming. Mattson, Sanders, and Massingill (2005).

Algorithm Structure Design Space

- Given a collection of concurrent tasks, what's the next step?
- Map tasks to units of execution (e.g., threads)

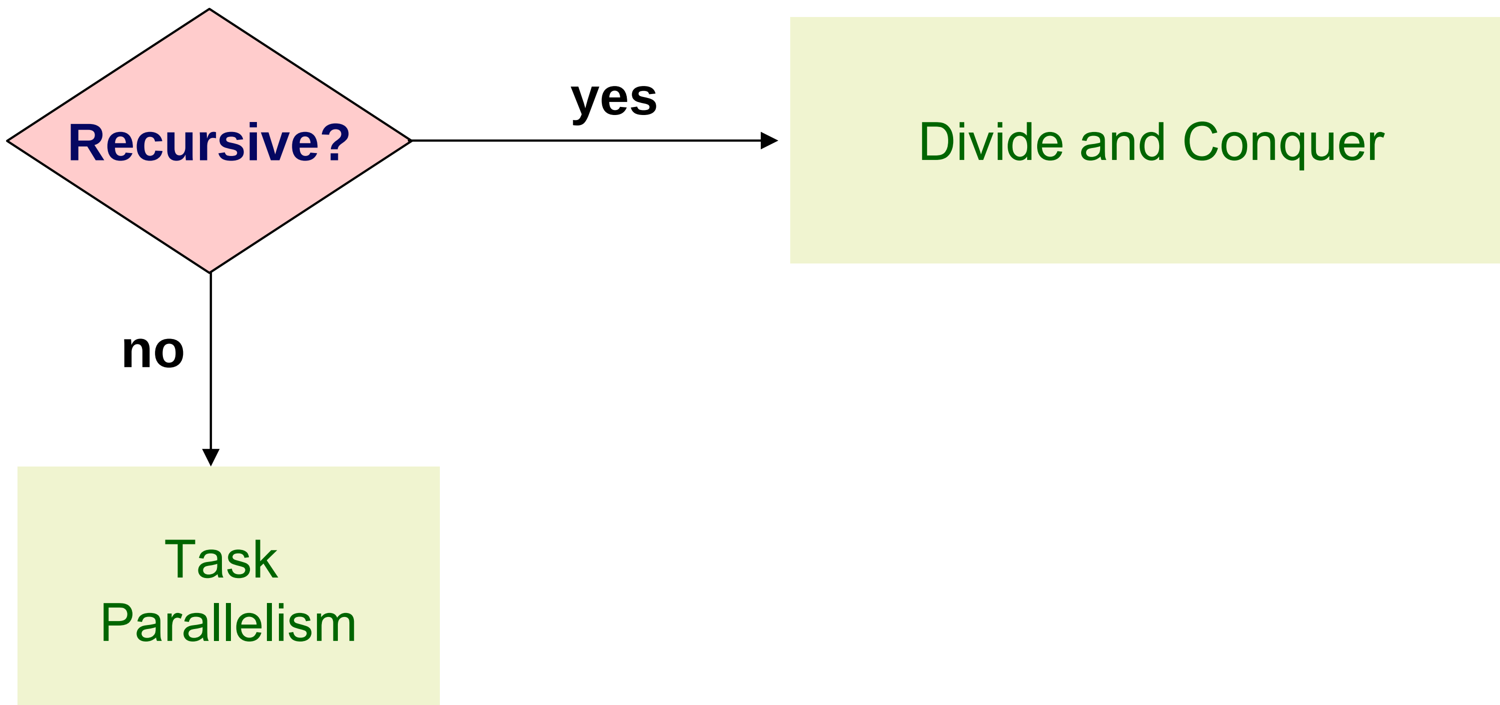
- Important considerations
  - Magnitude of number of execution units platform will support
  - Cost of sharing information among execution units
  - Avoid tendency to over constrain the implementation
    - Work well on the intended platform
    - Flexible enough to easily adapt to different architectures

Major Organizing Principle

- How to determine the algorithm structure that represents the mapping of tasks to units of execution?

- Concurrency usually implies major organizing principle
  - Organize by tasks
  - Organize by data decomposition
  - Organize by flow of data

Organize by Tasks?

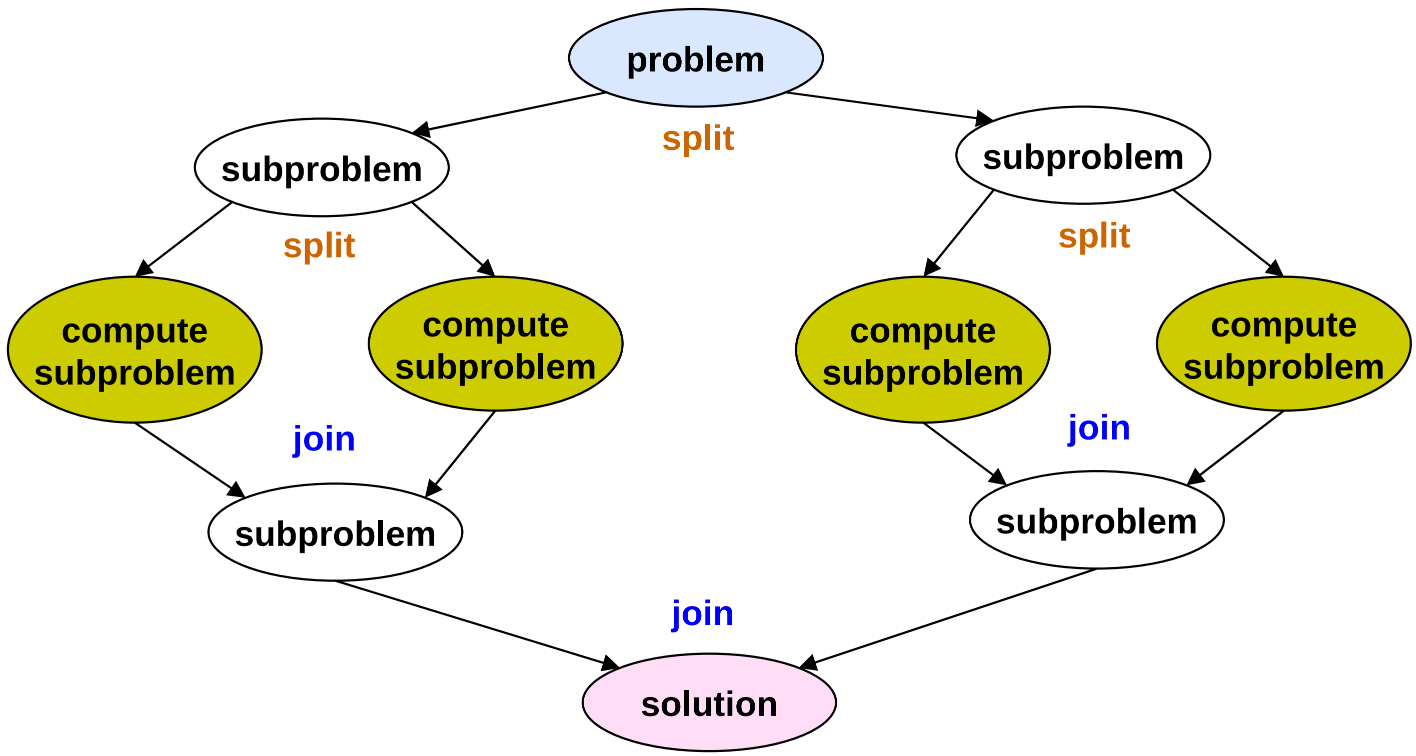


Task Parallelism

- Ray tracing
  - Computation for each ray is a separate and independent
- Molecular dynamics
  - Non-bonded force calculations, some dependencies
- Common factors
  - Tasks are associated with iterations of a loop
  - Tasks largely known at the start of the computation
  - All tasks may not need to complete to arrive at a solution

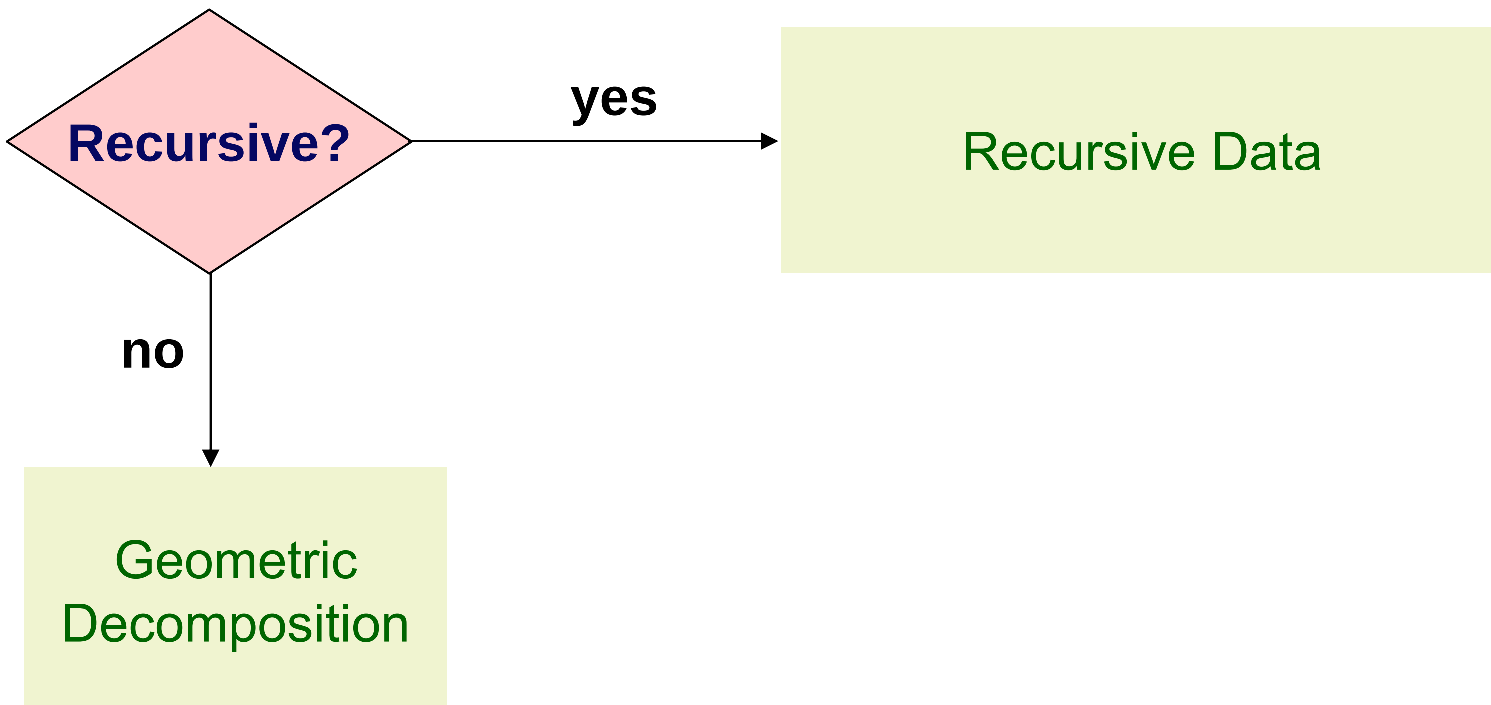
Divide and Conquer

- For recursive programs: divide and conquer
  - Subproblems may not be uniform
  - May require dynamic load balancing



Organize by Data?

- Operations on a central data structure
  - Arrays and linear data structures
  - Recursive data structures



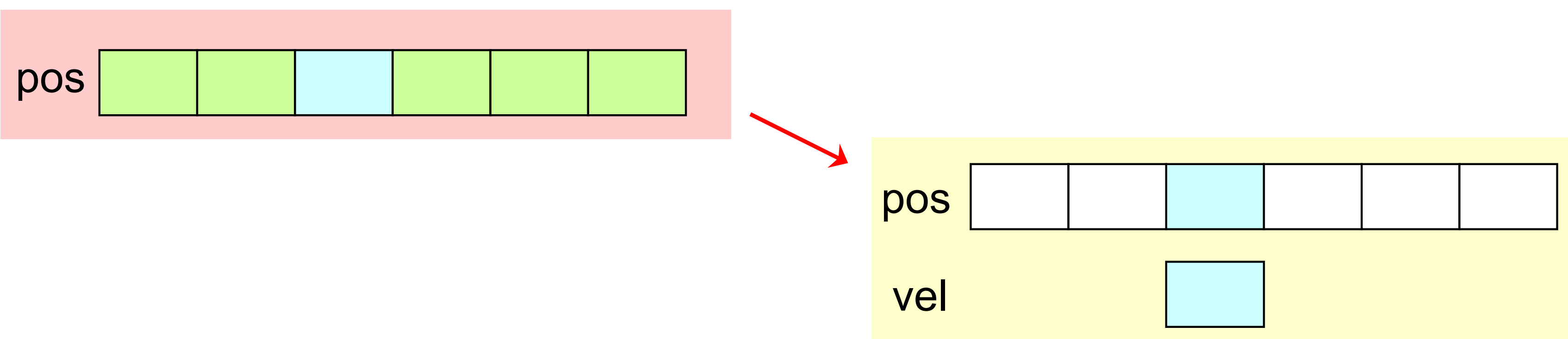
Geometric Decomposition

- Gravitational body simulator
  - Calculate force between pairs of objects and update accelerations

```
VEC3D acc[NUM_BODIES] = 0;

for (i = 0; i < NUM_BODIES - 1; i++) {
  for (j = i + 1; j < NUM_BODIES; j++) {
    // Displacement vector
    VEC3D d = pos[j] – pos[i];
    // Force
    t = 1 / sqr(length(d));
    // Components of force along displacement
    d = t * (d / length(d));

    acc[i] += d * mass[j];
    acc[j] += -d * mass[i];
  }
}
```



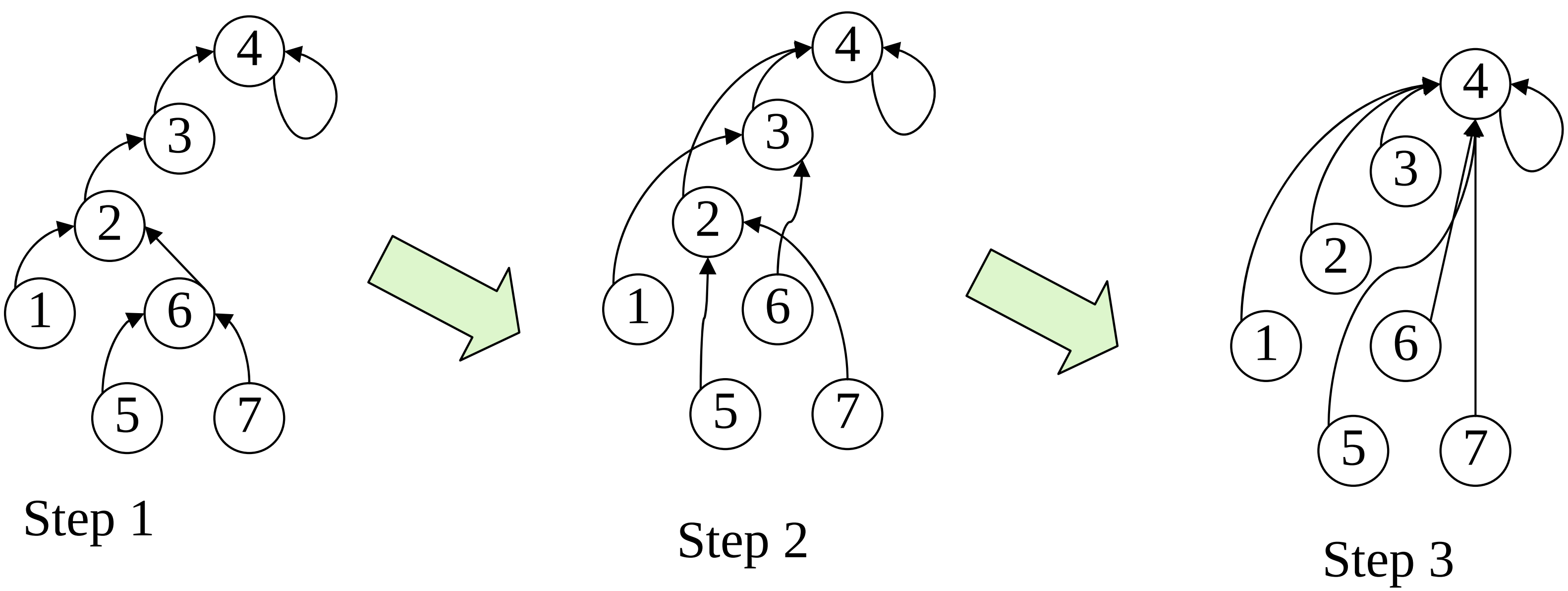
Recursive Data

- Computation on a list, tree, or graph
  - Often appears the only way to solve a problem is to sequentially move through the data structure

- There are however opportunities to reshape the operations in a way that exposes concurrency

Recursive Data Example: Find the Root

- Given a forest of rooted directed trees, for each node, find the root of the tree containing the node
  - Parallel approach: for each node, find its successor's successor, repeat until no changes
    - O(log n) vs. O(n)



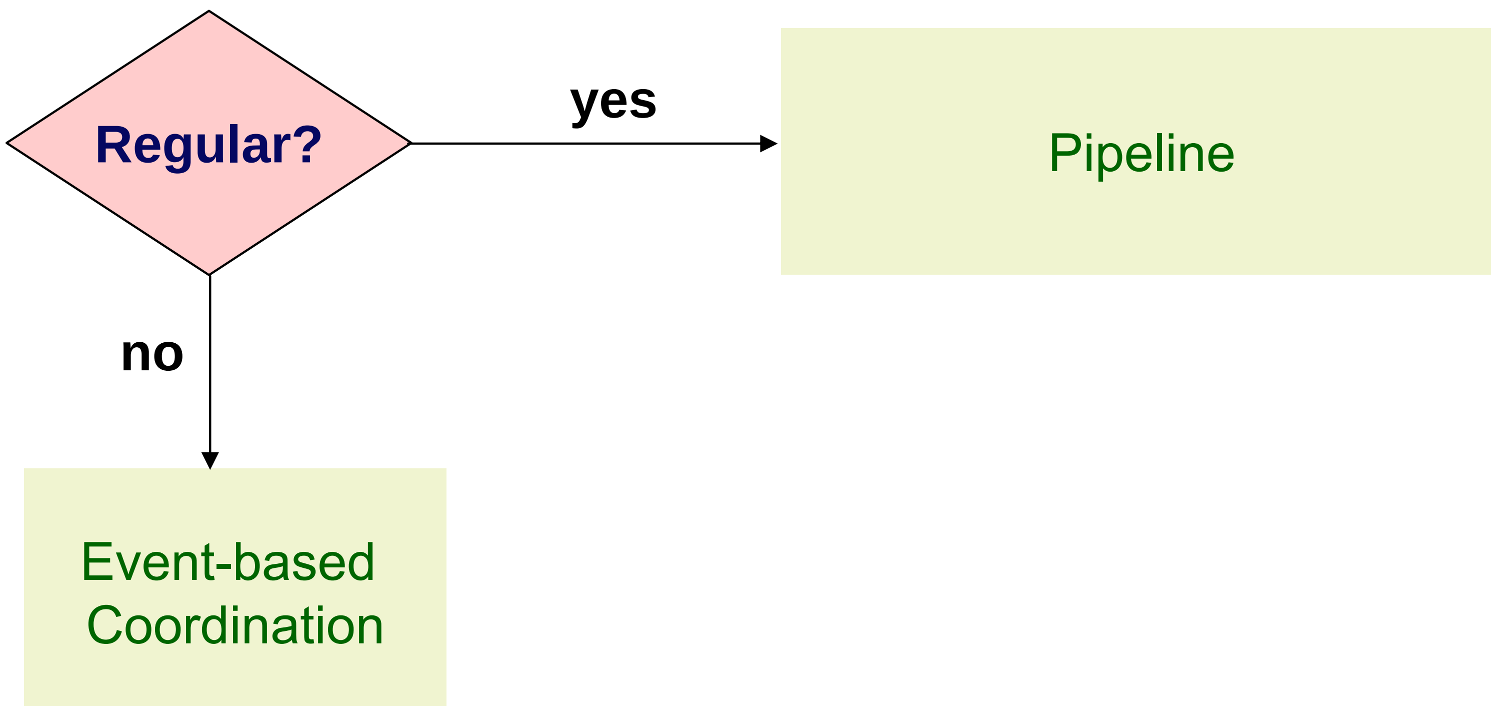
Work vs. Concurrency Tradeoff

- Parallel restructuring of find the root algorithm leads to O(n log n) work vs. O(n) with sequential approach

- Most strategies based on this pattern similarly trade off increase in total work for decrease in execution time due to concurrency

Organize by Flow of Data?

- In some application domains, the flow of data imposes ordering on the tasks
  - Regular, one-way, mostly stable data flow
  - Irregular, dynamic, or unpredictable data flow



Pipeline Throughput vs. Latency

- Amount of concurrency in a pipeline is limited by the number of stages
- Works best if the time to fill and drain the pipeline is small compared to overall running time
- Performance metric is usually the throughput
  - Rate at which data appear at the end of the pipeline per time unit (e.g., frames per second)
- Pipeline latency is important for real-time applications
  - Time interval from data input to pipeline, to data output

Event-Based Coordination

- In this pattern, interaction of tasks to process data can vary over unpredictable intervals

- Deadlocks are likely for applications that use this pattern

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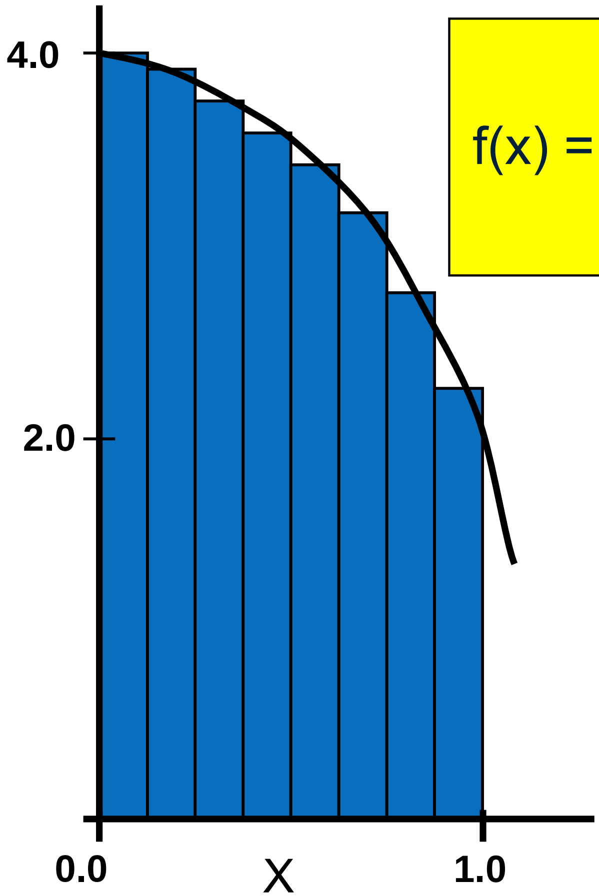
Supporting Structures

- SPMD
- Loop parallelism
- Master/Worker
- Fork/Join

SPMD Pattern

- Single Program Multiple Data: create a single source-code image that runs on each processor
  - Initialize
  - Obtain a unique identifier
  - Run the same program each processor
    - Identifier and input data differentiate behavior
  - Distribute data
  - Finalize

Example: Parallel Numerical Integration

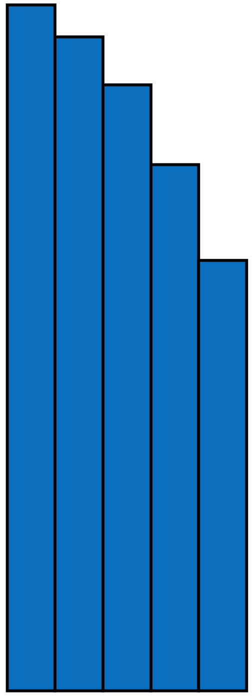


$$f(x) = \frac{4.0}{(1+x^2)}$$

```
static long num_steps = 100000;

void main()
{
    int i;
    double pi, x, step, sum = 0.0;

    step = 1.0 / (double) num_steps;
    for (i = 0; i < num_steps; i++){
        x = (i + 0.5) * step;
        sum = sum + 4.0 / (1.0 + x*x);
    }

    pi = step * sum;
    printf("Pi = %f\n", pi);
}
```

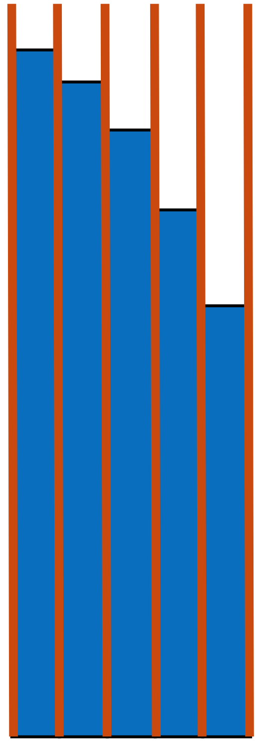
Computing Pi With Integration (MPI)

```
static long num_steps = 100000;

void main(int argc, char* argv[])
{
   int i_start, i_end, i, myid, numprocs;
   double pi, mypi, x, step, sum = 0.0;

   MPI_Init(&argc, &argv);
   MPI_Comm_size(MPI_COMM_WORLD, &numprocs);
   MPI_Comm_rank(MPI_COMM_WORLD, &myid);

   MPI_BCAST(&num_steps, 1, MPI_INT, 0, MPI_COMM_WORLD);

   i_start = my_id * (num_steps/numprocs)
   i_end = i_start + (num_steps/numprocs)

   step = 1.0 / (double) num_steps;

   for (i = i_start; i < i_end; i++) {
        x = (i + 0.5) * step
        sum = sum + 4.0 / (1.0 + x*x);
   }
   mypi = step * sum;

   MPI_REDUCE(&mypi, &pi, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD);

   if (myid == 0)
        printf("Pi = %f\n", pi);

   MPI_Finalize();
}
```



Block vs. Cyclic Work Distribution

```
static long num_steps = 100000;

void main(int argc, char* argv[])
{
   int i_start, i_end, i, myid, numprocs;
   double pi, mypi, x, step, sum = 0.0;

   MPI_Init(&argc, &argv);
   MPI_Comm_size(MPI_COMM_WORLD, &numprocs);
   MPI_Comm_rank(MPI_COMM_WORLD, &myid);

   MPI_BCAST(&num_steps, 1, MPI_INT, 0, MPI_COMM_WORLD);

   i_start = my_id * (num_steps/numprocs)
   i_end = i_start + (num_steps/numprocs)

   step = 1.0 / (double) num_steps;

   for (i = myid; i < num_steps; i += numprocs) {
        x = (i + 0.5) * step
        sum = sum + 4.0 / (1.0 + x*x);
   }
   mypi = step * sum;

   MPI_REDUCE(&mypi, &pi, 1, MPI_DOUBLE, MPI_SUM, 0, MPI_COMM_WORLD);

   if (myid == 0)
        printf("Pi = %f\n", pi);

   MPI_Finalize();
}
```



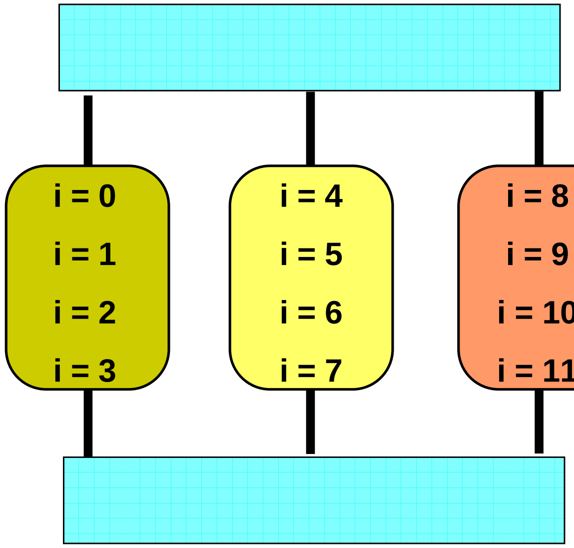
SPMD Challenges

- Split data correctly
- Correctly combine the results
- Achieve an even distribution of the work
- For programs that need dynamic load balancing, an alternative pattern is more suitable

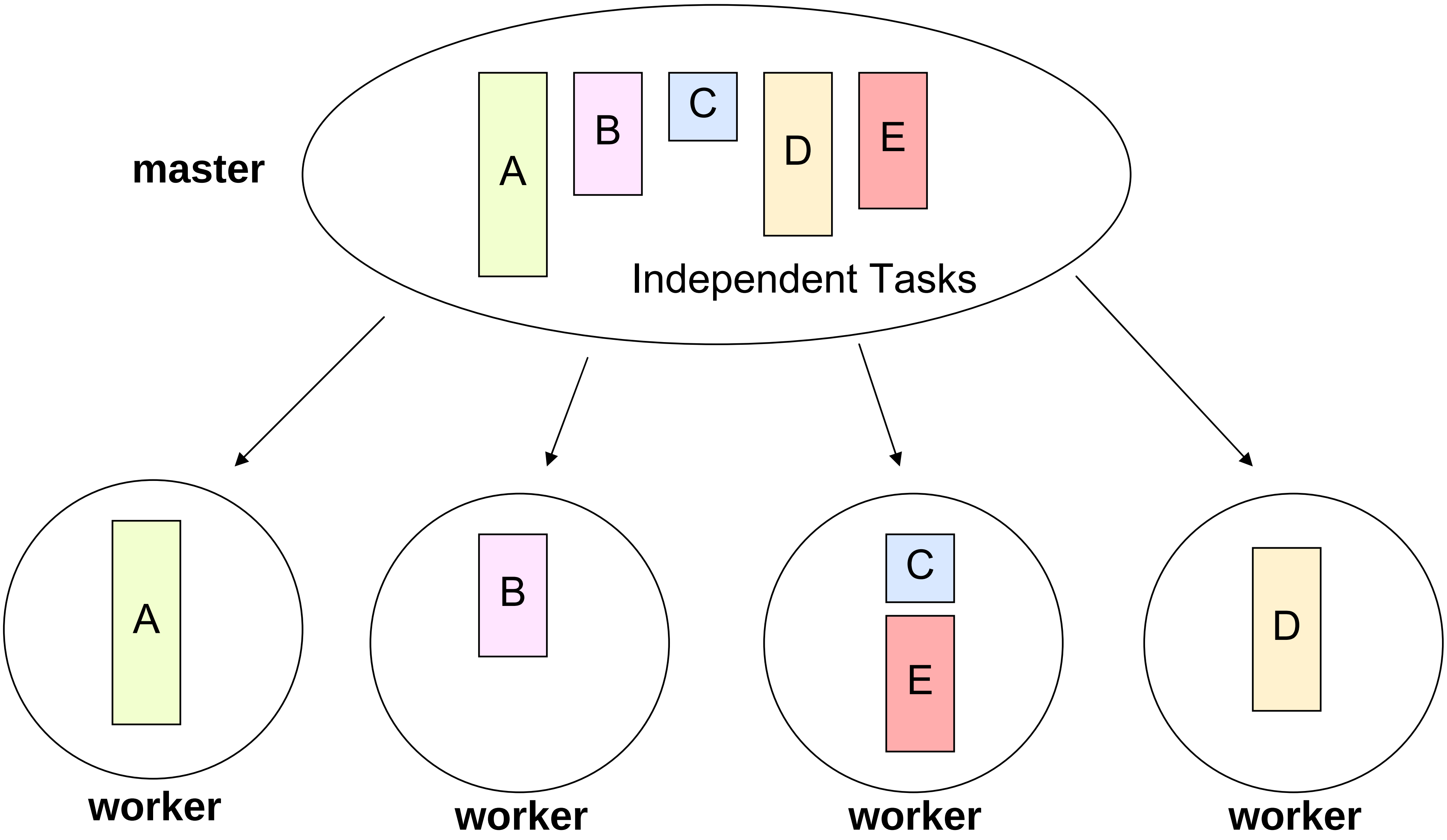
Loop Parallelism Pattern

- Many programs are expressed using iterative constructs
  - Programming models like OpenMP provide directives to automatically assign loop iteration to execution units
  - Especially good when code cannot be massively restructured

```
#pragma omp parallel for
for(i = 0; i < 12; i++)
      C[i] = A[i] + B[i];
```



Master/Worker Pattern



Master/Worker Pattern

- Particularly relevant for problems using task parallelism pattern where task have no dependencies
  - Embarrassingly parallel problems
- Main challenge in determining when the entire problem is complete

Fork/Join Pattern

- Tasks are created dynamically
  - Tasks can create more tasks
- Manages tasks according to their relationship
- Parent task creates new tasks (fork) then waits until they complete (join) before continuing on with the computation

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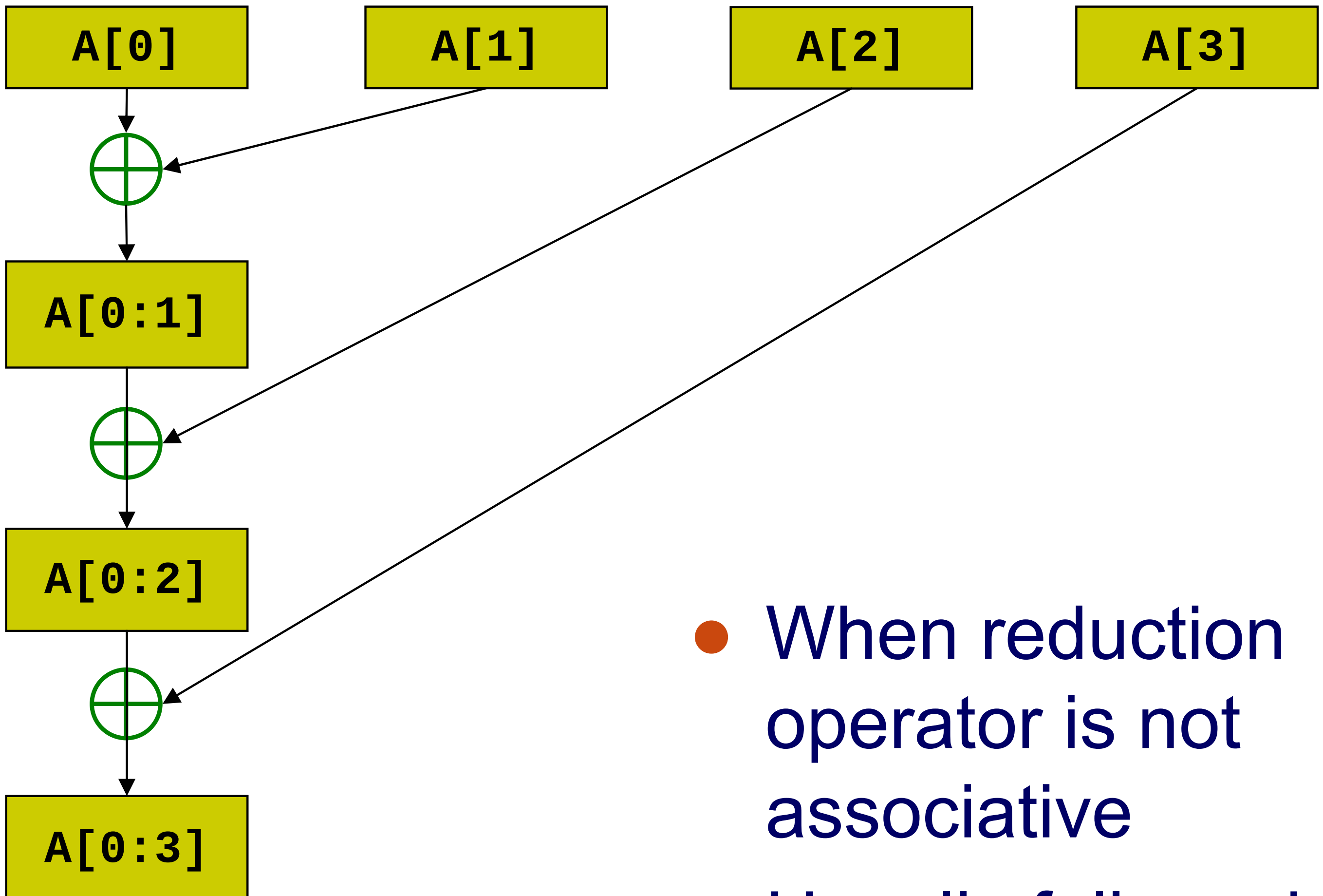
Communication Patterns

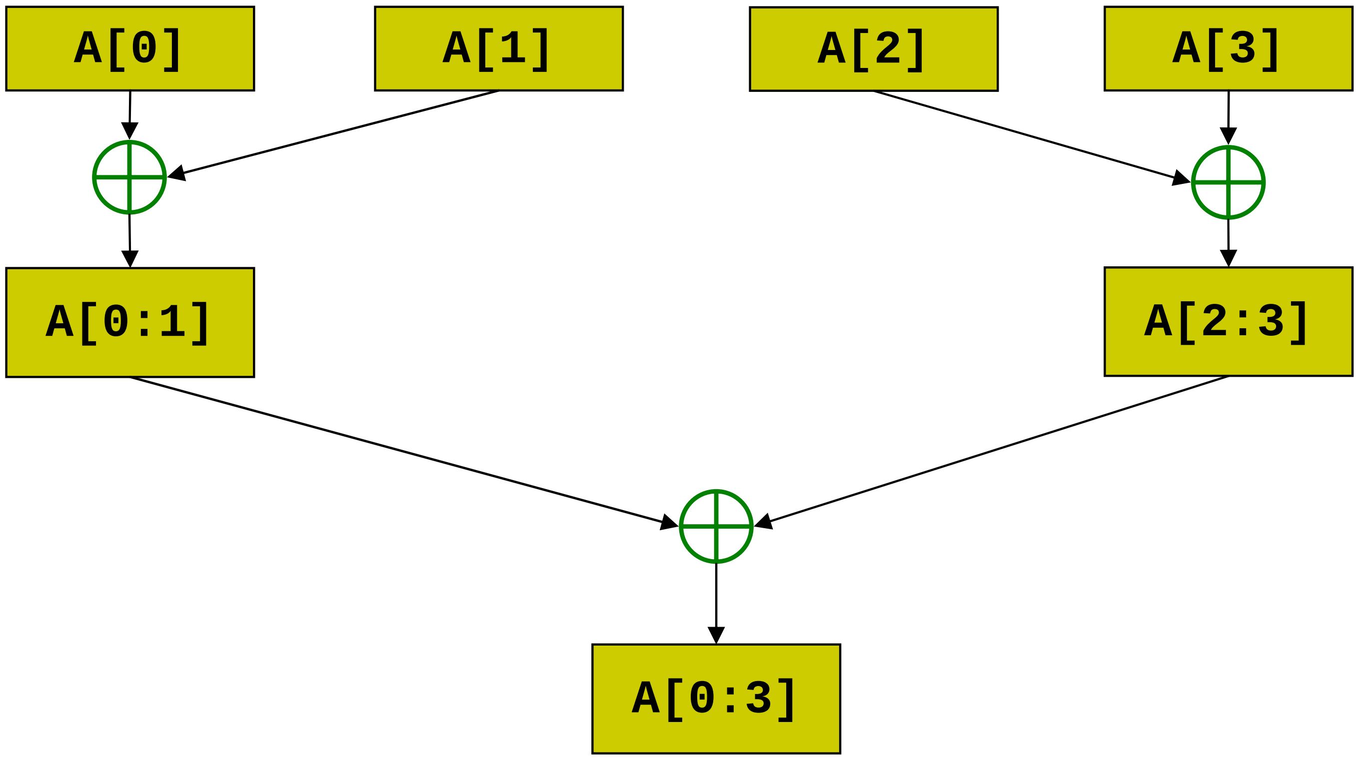
- Point-to-point
- Broadcast
- Reduction

Serial Reduction



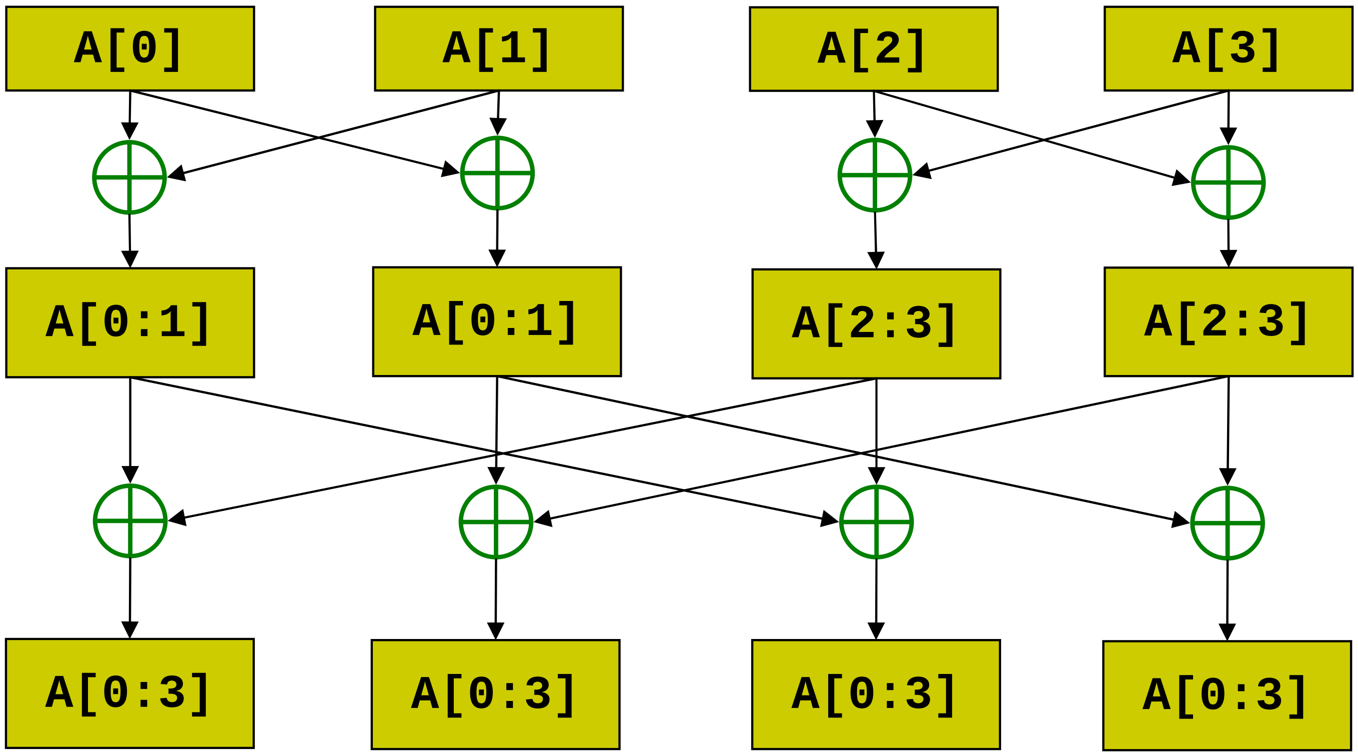
- When reduction operator is not associative
- Usually followed by a broadcast of result

Tree-based Reduction



- n steps for 2^n units of execution
- When reduction operator is associative
- Especially attractive when only one task needs result

Recursive-doubling Reduction



- n steps for 2^n units of execution
- If all units of execution need the result of the reduction

Recursive-doubling Reduction

- Better than tree-based approach with broadcast
  - Each units of execution has a copy of the reduced valut at the end of n steps
  - In tree-based approach with broadcast
    - Reduction takes n steps
    - Broadcast cannot begin until reduction is complete
    - Broadcast takes n steps (architecture dependent)
    - O(n) vs. O(2n)

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Summary

Algorithm Structure and Organization

	Task parallelism	Divide and conquer	Geometric decomposition	Recursive data	Pipeline	Event-based coordination
SPMD	****	***	****	**	***	**
Loop Parallelism	****	**	***			
Master/ Worker	****	**	*	*	****	*
Fork/ Join	**	****	**		****	****

- Patterns can be hierarchically composed so that a program uses more than one pattern